Susceptibility of Existing and Proposed Areas of Conservation and the Species within their Boundaries to Climate-Based Change in the Scotian Shelf-Bay of Fundy Bioregion

By

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## 1.0. Introduction

The need to protect our oceans becomes ever more important as the effects of climate change worsen. The impacts of climate change on the global ocean are pervasive, manifesting through direct changes to the physical environment including changes in sea surface temperature (SST), acidification and oxygen depletion (Lotterhos et al., 2021) and indirect effects on ecological systems responding to these physical changes. These indirect effects include changes in productivity (REF), biodiversity (REF) and ecosystem function (REF), all of which are foundational elements of the marine environment. Hence the mitigation of climate change is integral to maintain the health of our oceans. However, many other elements of anthropomorphic life also threaten the ocean's well-being and biodiversity. Protecting ocean ecosystems from other stressors including overfishing and pollution can also contribute to enhanced resilience in the face of climate change.

One way Canada is taking action against climate change is through the protection of marine and coastal areas. With the renewal of the Marine Conservation Targets Program, Canada’s goal is to have 30% of its coastal/marine areas protected by 2030. This will be achieved through the implementation of Marine Protected Areas (MPAs) and other effective area-based conservation measures (OECMs) (DFO, 2021). MPAs in Canada are areas of the ocean that are legally protected to help ensure the conservation of marine ecosystems and species. They may be designated due to the presence of special natural features (e.g., unique and productive habitats or diversity hotspots), concentrations of species at risk (e.g., endangered or threatened species under the Canadian Species At Risk Act), and /or due to environmental, cultural and socio-economic importance (DFO, 2018). MPAs in Canada are administered by the Federal Department of Fisheries and Oceans (DFO). Their boundaries are decided based on the priorities of various ocean stakeholders (i.e., fisheries, aboriginal communities/organizations, ocean industries, federal and provincial government, conservation groups, coastal communities, etc.). The primary goal of the Canadian Marine Conservation Network (a collection of MPAs and OECMs across the nation’s marine bioregions) is to “*provide long-term protection of marine biodiversity, ecosystem function and special natural features*” with specific objectives developed according to the unique physical, ecological and biological attributes of each area (Government of Canada, 2005). With that being said, dynamic ecological changes anticipated due to climate change will threaten the ability of some MPAs and their respective networks to achieve their conservation objectives, potentially necessitating changes to site-level management or boundaries, or the configuration of the conservation network as a whole.

Some countries, largely those with protections in place for coral reef ecosystems, have begun adapting their MPA management plans for climate change (Wilson et al., 2020). The addition of climate change considerations to MPA management programs, however, has not been uniform, and is particularly lacking in higher-latitude systems like Canada (Tittensor et al., 2019, O’Regan et al., 2021, Bryndum-Buchholz et al. 2022). Climate change has most often been considered in the design phase for MPA networks. The most popular design strategies include climate-smart conservation (CSC; Stein et al., 2014) and systematic conservation planning (SCP; Mačić et al., 2018). Other design approaches not as widely implemented include adaptation for conservation targets (ACT), portfolio decision analysis (PDA), and the IUCN adaptation cycle (Wilson et al., 2020). Though these strategies differ, they employ similar practical methods to be incorporated within MPA management design and planning. Summarizing existing climate-smart MPA network design strategies and providing further advice on strategies to fully integrate climate change considerations into MPA management programs, Wilson et al. (2020) suggested the following four steps be taken:

1. set conservation goals and MPA objectives that can be adapted/shifted as necessary due to climate change,
2. apply vulnerability assessments to evaluate how climate change may affect the ecosystems or species within the MPAs in the future,
3. incorporate climate change adaptations into MPA design based on results from the vulnerability assessments (e.g., protection of climate refugia), and
4. assess the MPAs continually to ensure their effectiveness in achieving their conservation goals and resistance to climate change.

Other practical climate change adaptations that have been suggested in MPA management and design include increasing species’ resilience through protection from other stressors, protecting future habitat, increasing connectivity, and protecting representative examples of a wide variety of habitats and ecological communities to support broader ecosystem resilience (DFO, 2018; DFO, 2020; Wilson et al., 2020). If implemented, these steps and concepts should help to ensure that MPAs and MPA networks are best positioned to continue to protect marine biodiversity and maintain their effectiveness as temperatures and other hydrographic properties evolve due to climate change.

A species’ distribution is constrained by the physical and environmental conditions they require for survival and their interactions with other species – a species’ niche. For many marine taxa, distribution can be, for the most part, controlled by temperature and depth, where temperature tolerance is determined by metabolic demands (Fry, 1971). Physiologically, narrower temperature tolerance in ectothermic organisms, like fish, is largely because they acquire oxygen directly from surrounding waters into their tissues through their gills. Endothermic, air-breathing marine mammals tend to have larger thermal tolerance niches because they do not acquire oxygen directly from the water around them (Pörtner & Farrell, 2008) and have the ability to behaviourally thermoregulate (Vaudo et al., 2016). When an organism is living at its upper or lower temperature limit, oxygen demand increases, often exceeding the organism’s ability to maintain it, causing reduced performance in ventilation and circulation (Pörtner, 2001). This can lead to reduced activity, feeding, growth, and reproductive fitness. In some cases, and over evolutionary time scales, adaptation to novel environmental conditions is possible. However, evidence suggests that the rapid environmental changes associated with climate change are already causing geographic shifts in distribution that track shifting distributions of species’ thermal niches (Pinsky et al., 2013; Crozier & Hutchings, 2014; Pinsky et al., 2021).

The species-specific thermal niche is an important consideration when predicting how species’ distribution will respond to changing environmental conditions. This can be demonstrated by how cold-water species generally respond negatively to warmer winters, while warm-water species respond positively to warmer winters (Pinsky et al., 2021). The timing of a species’ distributional response is a product of the species’ thermal niche and the chronology of change (e.g., warming) associated with climate change. The term ‘time of emergence’ can be defined as the year in which SST exceeds a species’ upper thermal tolerance in a particular area of interest (Henson et al., 2017). As species shift towards the poles and into deeper, cooler waters (Pinsky et al., 2020), species of conservation concern may eventually emerge from their thermal niche within the MPAs, and other conservation areas, originally designated for their protection. The regional network of MPAs and other effective area-based conservation measures (OECMs) proposed for the Scotian Shelf, off Canada’s eastern coast (Figure 1) was designed without any explicit consideration for the impacts of climate change (DFO, 2018). To ensure this design is resilient to climate change, it is imperative to first assess the time of emergence of species of conservation value within the proposed site boundaries. Sites can then be prioritized for designation as MPAs accordingly, and sites that may require redesign (e.g., shifting boundaries or exclusion from the draft network) can be identified. Maybe put a sentence here about how this connects to Wilson et al.’s advice….

Add Figure 1 here, unless Dal standard is to put all tables and figures at the end…

The aim of this study is to estimate the time of emergence of 30 fish and invertebrate species of interest (depleted species, species at risk, and commercially important species) within each of the existing and proposed MPA/OECM site boundaries in the draft conservation network design for the Scotian Shelf (Figure 1) under six projections of future sea surface temperature. Time of emergence overall should depend both on the emissions scenario (time of emergence is inversely proportional to the speed of warming) and the range of a species thermal niche, whereby those species with more restricted thermal niches are more likely to experience habitat shifts, and for those shifts to happen sooner. The idea of using the time of emergence in the planning of MPAs is novel and can be used to inform on how the future effectiveness of MPAs and MPA Networks could change as species distributions and ecosystems shift. This information may help MPA managers to prioritize sites for immediate designation and to identify sites that may require more adaptive management strategies due to predicted shifts in priority species distributions. The importance of MPAs is great, not only for the ocean’s biodiversity and ecosystems but also for human societies, which benefit from the nutrition and other ecosystem services the ocean provides. The overall productivity of the ocean impacts the entire world from humans to marine species to marine ecosystems and it must be properly protected.

## 2.0. Methods

### 2.1. Species selection

Species from major marine taxa (e.g., piscivores, decapods, benthivores, plankton, etc.) were chosen to represent a cross-section of potential responses to climate change from species with varying traits. Species from these groupings were prioritized/selected based on their vulnerability status (e.g., Endangered, threatened, or special concern COSEWIC-listed species (COSEWIC, 2021)), commercial usage (e.g., Fishing industry; Rozalska & Coffen-Smout., 2020), and ecological importance (e.g., food source, keystone species, etc.; (Shackell et al., 2013; Stortini et al., 2015)). Species selection was informed from regional reports that conducted similar prioritization exercises (Stortini et al., 2015; Shackell et al., 2021; DFO, 2018). A full list of species and their selection criteria/grouping is available in Table 1.

**Table 1**. Selected species of the study including their common name, scientific name, importance (why the species was included), temperature niche (species 10th and 90th percentile temperature range) and depth niche (species 10th and 90th percentile depth range).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Common Name** | **Scientific Name (Genus, species)** | **Importance** | **Lower Temperature (10th percentile, °C)** | **Upper Temperature (90th percentile, °C)** | **Lower Depth (10th percentile, m)** | **Upper Depth (90U Upper Depth (90th percentile, m)**  **Dd** |
| American lobster | *Homarus americanus* | Commercial fish | 0 | 22 | 4 | 50 |
| American plaice | *Hippoglossoides platessoides* | Commercial fish/ Endangered | -1 | 11.4 | 59.7 | 350.5 |
| (ESS/WSS) Atlantic cod | *Gadus morhua* | Commercial fish/ Endangered | 4.15 | 13 | 20 | 339 |
| Atlantic halibut | *Hippoglossus hippoglossus* | Commercial fish | 2.23 | 10.87 | 58.5 | 864 |
| Atlantic wolffish | *Anarhichas lupus* | Special concern | 2.01 | 10.1 | 1 | 500 |
| Basking shark | *Cetorhinus maximus* | Endangered species | 8.71 | 21.14 | 0 | 834 |
| Blue whale | *Balaenoptera musculus* | Endangered species | -1.3 | 27.88 | 1000 | 4000 |
| Copepod (1) | *Calanus glacialis* | Important food source | -1.5 | 6 | 7.5 | 210 |
| Copepod (2) | *Calanus finmarchicus* | Important food source | 0.06 | 13.9 | 7.5 | 1221 |
| Common shortfin squid | *Illex illecebrosus* | Important food source | 5.51 | 18.07 | 57.6 | 434 |
| Cusk | *Brosme brosme* | Endangered species | 5.55 | 11.9 | 18 | 549 |
| (ESS/WSS) haddock | *Melanogrammus aeglefinus* | Commercial fish | 1 | 13 | 10 | 220 |
| Little skate | *Leucoraja erinacea* | Sensitive population | 8.47 | 17.04 | 32 | 152 |
| Loggerhead turtle | *Caretta caretta* | Vulnerable species | 15.31 | 27.9 | 0 | 250 |
| Monkfish | *Lophius americanus* | Commercial fish/Sensitive population | 6.42 | 18.33 | 60.55 | 352 |
| North Atlantic Right whale | *Eubalaena glacialis* | Critically Endangered | 7.94 | 23.94 | 0 | 200 |
| Northern Bottlenose whale | *Hyperoodon ampullatus* | Depleted species | 3.57 | 19.32 | 1000 | 2000 |
| Northern shrimp | *Pandalus borealis* | Commercial fish | 0 | 14 | 50 | 500 |
| (ESS/WSS) pollock | *Pollachius virens* | Commercial fish/Sensitive population | 7.13 | 12.26 | 46 | 244.5 |
| Porbeagle shark | *Lamna nasus* | Vulnerable species | 8.03 | 22.18 | 0 | 1592 |
| Redfish species (1) | *Sebastes fasciatus* | Commercial fish/ Endangered | 3 | 11.92 | 63 | 366 |
| Redfish species (2) | *Sebastes mentella* | Commercial fish/ Endangered | 0.53 | 5.9 | 127 | 791 |
| Smooth skate | *Malacoraja senta* | Special concern | 4.19 | 11.38 | 84 | 426 |
| Snow crab | *Chionoecetes opilio* | Commercial fish | -1 | 9.28 | 77.5 | 373 |
| Spiny dogfish | *Squalus acanthias* | Commercial fish/ Threatened | 8.19 | 19.45 | 39 | 300 |
| Thorny skate | *Amblyraja radiata* | Special concern | 0.37 | 11.22 | 25 | 440 |
| White hake | *Urophycis tenuis* | Commercial fish/ Threatened | 5.91 | 15.32 | 59 | 397 |
| White shark | *Carcharodon carcharias* | Vulnerable species | 12.62 | 26.93 | 0 | 250 |
| Winter skate | *Leucoraja ocellata* | Threatened | 6.85 | 15.44 | 12 | 138 |
| Witch flounder | *Glyptocephalus cynoglossus* | Commercial fish/Sensitive population | 4.31 | 12.76 | 45 | 486 |

### 2.2. Species thermal and depth niche characterization

Species’ temperature niches (10th and 90th percentiles’) were first taken from the online global database Aquamaps (Aquamaps, 2021). These were further adapted to fit some species’ ecotypes found along the Scotian shelf (Shackell et al., 2013) including American lobster (*Homarus americanus*), American plaice (*Hippoglossoides platessoides*), Atlantic cod (*Gadus morhua*), Atlantic halibut (Hippoglossus hippoglossus), Haddock (*Melanogrammus aeglefinus*), Northern shrimp (*Pandalus borealis*), Redfish sp. (*Sebastes fasciatus*), and Snow crab (*Chionoecetes opilio*). The temperature ranges from Aquamaps and Shackell et al. (2013) were combined (Table 1) to capture the most realistic upper thermal limit based on the species physiology, but also ensuring that its current distribution in the cold region of interest was captured by using the lower limit given by Shackell et al. (2013).

The species depth niches (10th and 90th percentiles), at which a species has been observed within the Northwest Atlantic Ocean, were obtained from the online databases Aquamaps and OBIS (Aquamaps, 2021; OBIS, 2021). The largest depth range was created using the depth ranges from Aquamaps and OBIS combined in order to have the most representative depth niche for each species. Network sites were cropped to each species’ depth niche in R (RStudio Team, 2021).

Insert niche plots here.

### 2.3. Niche-informed network

The study area of this project is the Scotian Shelf-Bay of Fundy bioregion for which a network of existing and potential MPAs and OECMs has been identified (Figure 1). Polygons for each MPA/OECM in the proposed network were developed through an objective drive systematic conservation planning process using MARXAN (DFO, 2018) and through stakeholder consultation. A shapefile containing the site boundaries was obtained from DFO Maritimes Region Marine Planning and Conservation Section. For each species, a revised network was derived from this draft network based on expected residency and the depth niche for each species. Residency was determined based on querying OBIS for the last 20 years for any observations within a 25km buffer inclusive of the site. Those sites where residency is expected were then constrained to only the area within the specified depth range (Table 1), based on overlays the General Bathymetric Chart of the Oceans (GEBCO, 2021). From these residency and depth constraints species niche-informed networks were created and informed the basis for the remaining analyses.

The geographic polygons representing each MPA site were overlaid on 0.25-degree gridded temperature projection data (CMIP6 monthly averages) obtained from the World Climate Research Program (WCRP, 2021) to characterize species’ distributions within site boundaries over space and time. The percentage of grid cells within the species niche-informed network sites were compared between present day and projected future years. Year of thermal emergence was assessed for each grid cell that fell within the species’ depth niche, within each network site where the species has ever been observed within the past two decades (species observations inclusive of Jan 2000 to current were obtained from the Ocean Biodiversity Information System (OBIS)- OBIS, 2021).

### 2.4. Climate projections and time of thermal emergence

Time of emergence (ToE) is derived as the year that the average temperature during the warmest month exceeded a species’ upper thermal tolerance limit, and this exceedance continued for a period of at least four consecutive years thereafter (as per Boyce et al. *in review*). The year of thermal emergence was estimated for each grid cell that fell within a species’ depth niche, within each site where the species has been observed at least once since 1950 (see section 2.1), for each of 3 climate models (Table 2) under two emissions scenarios (IPCC, 2000): SSP1 RCP2.6 (best-case scenario where carbon emissions start declining now) and SSP5 RCP8.5 (worst-case scenario where carbon emissions continue increasing). Average monthly temperature projections for the time period 2020-2100 were obtained at a 0.25-degree resolution from the World Climate Research Program (WCRP, 2021) for each of the five climate models under both emissions scenarios (a total of ten time series of average monthly temperature projections).

**Table 2**. Climate change models used for analysis of both SSP1 2.6 and SSP5 8.5 climate scenarios and the institutions for which they are named.

|  |  |  |
| --- | --- | --- |
| Abbreviation | Name | Reference |
| AWI | Alfred Wegener Institute | (Semmler et al., 2020) |
| CNRM | Centre National de Recherches Météorologiques | (Moigne et al., 2016) |
| GFDL | Geophysical Fluid Dynamics Laboratory | (Delworth et al., 2012) |
| HAD | Hadley Centre Atmospheric | (Pope et al., 2000) |
| IPSL | Institut Piere-Simon Laplace | (Jiang et al., 2021) |

Time of emergence for each species in each grid cell was calculated as the average time of emergence across models for each emissions scenario; the standard deviation was also calculated to characterize uncertainty, i.e., variation among model projections. Within each network site, the year in which a species reached its average time of emergence in 100% of the cells within its depth niche was recorded as the site-level year of emergence for that species. The years in which the first species, 50% of the species, and 100% of the species emerged (on average) from a site were then calculated based on the individual species site-level time of emergence results. The years in which 1, 50%, and 100% of species emerged were then transformed into a map representation using R (RStudio Team, 2021).

3. Results

3.1. Climate Projections

Insert time series of temperature projections here and discuss differences between RCP’s and models.

3.2. Thermal stress across the conservation network

e.g., Results show a gradient of increased ToEs from west to east, and offshore to inshore across the bioregion (Figure 4). Generally, ToEs are sooner along the shelf edge, in the Boy of Fundy (BoF) and in the south-western reaches of the Scotian Shelf (Figure 4); 71% and 88% of WSS and BoF sites, respectively, lose more than 50% of species by 2100 under RCP 8.5 (Figure 5). Comparatively, only 2 of 10 ESS sites lose more than 50% of species by 2100 (Figure 5). Six of 8 BoF sites lose >50% by 2075. Under RCP 2.6, this variation between regions is maintained but the majority of sites lose <50% by 2100 (Figure 5).

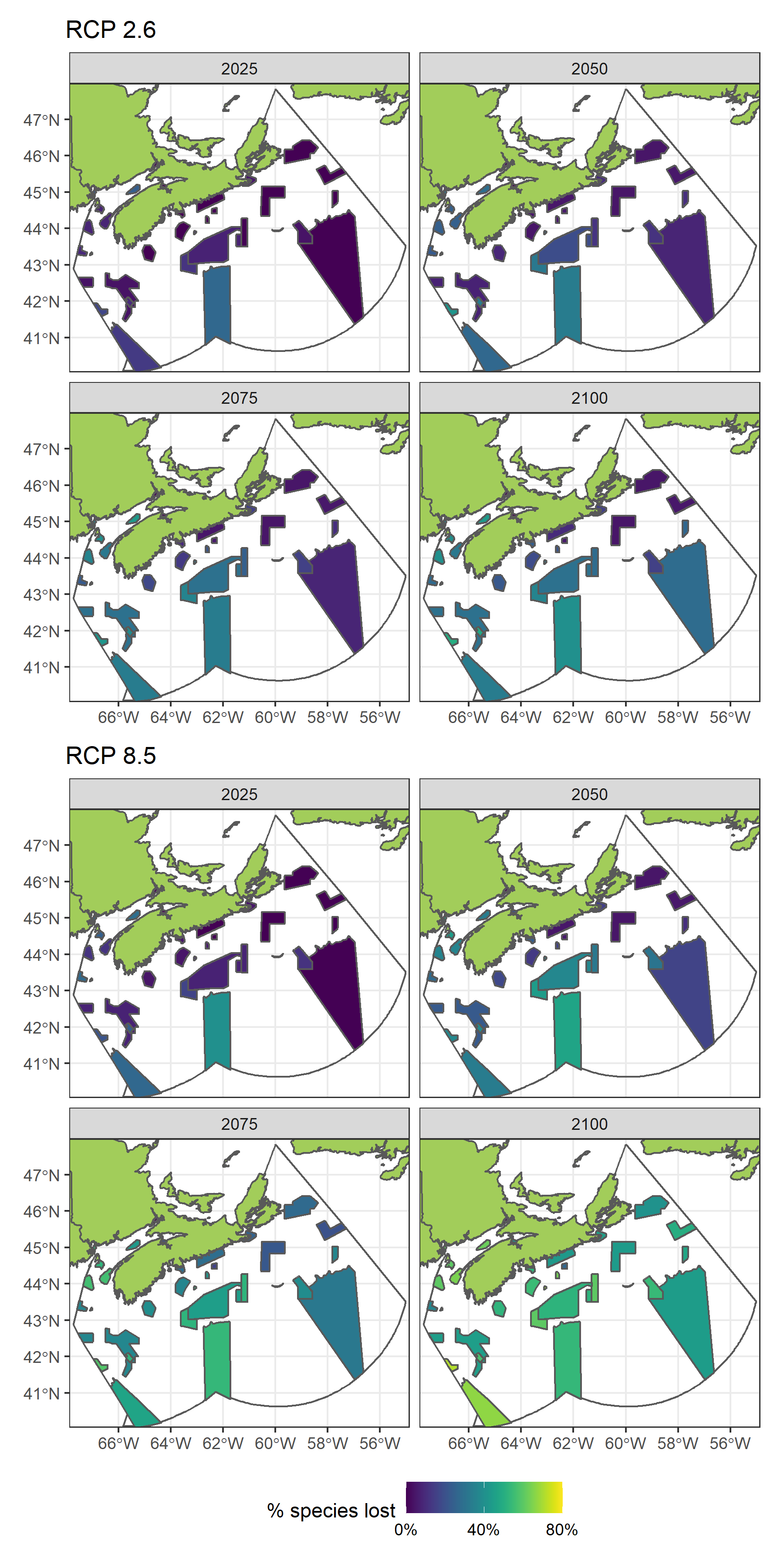


Figure 4. Comparison between emission scenarios RCP 2.6 and RCP 8.5 of the percentage of species lost (illustrated by a color spectrum of navy to yellow, where navy represents 0% species loss and yellow represents 100% species loss) for future years 2025, 2050, 2075, and 2100 of each MPA/OECM polygon on the Scotian shelf Bay of Fundy bioregion.

Chart

Description automatically generated

Figure 5. Comparison between emission scenarios RCP 2.6 and RCP 8.5 of the percentage of species lost for future years 2025 (purple), 2050 (blue), 2075 (green), and 2100 (yellow) of each MPA/OECM site (abbreviated titles on y-axis see Table 3 for full names) divided into there corresponding region (Bay of Fundy, Eastern Scotian shelf, and Western Scotian shelf) in the Scotian shelf Bay of Fundy bioregion.

3.3. Thermal stress of species

e.g., In general, results show a more rapid increase in thermal stress, i.e., proportion of habitat within the network sites becoming thermally stressful, over time under RCP 8.5 compared to RCP 2.6 (Figure 6). Under RCP 2.6., average habitat lost (or becoming intolerable) plateaus at just under 25% by 2080 (figure 6), indicating that many species will continue to find suitable habitat within the conservation network sites, even 60-80 years from now. Some species are more at risk of thermal stress than others. In particular, demersal fish lose X% more habitat to thermal stress on average compared to bentho-pelagic/pelagic fish, invertebrates, and other species (Figure 7). Species that are least likely to experience thermal stress in any of the network sites throughout the next 80 years even under RCP 8.5 include…. Important food sources for cetaceans and large fish, copepod, Calanus finmarchicus and northern shrimp, Pandalus borealis, show little thermal stress under RCP 2.6, but may lose more than 50% of habitat within the conservation network sites by 2075 due to thermal stress under the high-emissions scenario (Figure 7). Often, species X is the first to experience temperatures outside its thermal niche (i.e., to have the earliest time of emergence), particularly in X sites (Table 3).

Graphical user interface, chart

Description automatically generated

Figure 6. Comparison between emission scenarios RCP 2.6 and RCP 8.5 of the percentage of habitat lost for future years 2025 (purple), 2050 (blue), 2075 (green), and 2100 (yellow) averaged by climate models and species ToEs. The dashed lines represent the average of the climate models for each species.

A screenshot of a computer

Description automatically generated with medium confidenceYou need to add labels of species groups to this plot. Use code Ryan used to make Figure 5.

Figure 7. Comparison between emission scenarios RCP 2.6 and RCP 8.5 of the percentage of habitat lost (based on each species niche informed network within the Scotian shelf draft network of MPA/OECMs) for each species (grouped taxonomically) for future years 2025 (purple), 2050 (blue), 2075 (green), and 2100 (yellow).

Table 3. The first emerged species and their ToE for each emissions scenario at each MPA/OECM site in the Scotian shelf Bay of Fundy bioregion draft network.

|  |  |  |  |
| --- | --- | --- | --- |
| Site | Emissions scenario | Species | ToE |
| Bird Island | RCP 2.6 | *Anarhichas lupus* | 2050 |
| RCP 8.5 | *Anarhichas lupus* | 2041 |
| Brier Island | RCP 2.6 | *Chionoecetes opilio* | 2015 |
| RCP 8.5 | *Anarhichas lupus* | 2015 |
| Canso Ledges - Sugar Harbour Islands | RCP 2.6 | *Chionoecetes opilio* | 2025 |
| RCP 8.5 | *Chionoecetes opilio* | 2015 |
| Central Scotian Slope, Rise and Abyss | RCP 2.6 | *Anarhichas lupus* | 2015 |
| RCP 8.5 | *Amblyraja radiata* | 2015 |
| Chebogue | RCP 2.6 | *Anarhichas lupus* | 2027 |
| RCP 8.5 | *Anarhichas lupus* | 2015 |
| Corsair/Georges Canyons Conservation Area | RCP 2.6 | *Hippoglossus hippoglossus* | 2019 |
| RCP 8.5 | *Hippoglossus hippoglossus* | 2015 |
| Eastern Canyons | RCP 2.6 | *Anarhichas lupus* | 2035 |
| RCP 8.5 | *Chionoecetes opilio* | 2030 |
| Eastern Shoal | RCP 2.6 | *Chionoecetes opilio* | 2027 |
| RCP 8.5 | *Chionoecetes opilio* | 2029 |
| Eastern Shore Islands | RCP 2.6 | *Chionoecetes opilio* | 2035 |
| RCP 8.5 | *Chionoecetes opilio* | 2025 |
| Emerald Basin Sponge Conservation Area | RCP 2.6 | *Chionoecetes opilio* | 2027 |
| RCP 8.5 | *Chionoecetes opilio* | 2020 |
| Fundian Channel-Browns Bank | RCP 2.6 | *Chionoecetes opilio* | 2022 |
| RCP 8.5 | *Chionoecetes opilio* | 2015 |
| Georges Bank | RCP 2.6 | *Anarhichas lupus* | 2019 |
| RCP 8.5 | *Anarhichas lupus* | 2015 |
| Head Harbour, West Isles and The Passages | RCP 2.6 | *Amblyraja radiata* | 2015 |
| RCP 8.5 | *Amblyraja radiata* | 2015 |
| Horse Mussel Reefs | RCP 2.6 | *Amblyraja radiata* | 2015 |
| RCP 8.5 | *Amblyraja radiata* | 2015 |
| Jordan Basin Conservation Area | RCP 2.6 | *Anarhichas lupus* | 2015 |
| RCP 8.5 | *Amblyraja radiata* | 2015 |
| LaHave Basin | RCP 2.6 | *Chionoecetes opilio* | 2027 |
| RCP 8.5 | *Chionoecetes opilio* | 2018 |
| LaHave Islands | RCP 2.6 | *Amblyraja radiata* | 2068 |
| RCP 8.5 | *Amblyraja radiata* | 2048 |
| Long Eddy | RCP 2.6 | *Amblyraja radiata* | 2015 |
| RCP 8.5 | *Amblyraja radiata* | 2015 |
| Lophelia Coral Conservation Area | RCP 2.6 | *Anarhichas lupus* | 2035 |
| RCP 8.5 | *Chionoecetes opilio* | 2030 |
| Machias Seal Island Migratory Bird Sanctuary | RCP 2.6 | *Amblyraja radiata* | 2027 |
| RCP 8.5 | *Amblyraja radiata* | 2015 |
| Middle Bank-Canso Bank | RCP 2.6 | *Chionoecetes opilio* | 2035 |
| RCP 8.5 | *Chionoecetes opilio* | 2039 |
| Misaine Bank and Laurentian Channel | RCP 2.6 | *Chionoecetes opilio* | 2044 |
| RCP 8.5 | *Chionoecetes opilio* | 2029 |
| North of Emerald Basin Sea Pen Field | RCP 2.6 | *Chionoecetes opilio* | 2035 |
| RCP 8.5 | *Chionoecetes opilio* | 2025 |
| Northeast Channel Coral Conservation Area | RCP 2.6 | *Anarhichas lupus* | 2017 |
| RCP 8.5 | *Anarhichas lupus* | 2015 |
| Northern Gulf of Maine | RCP 2.6 | *Anarhichas lupus* | 2015 |
| RCP 8.5 | *Anarhichas lupus* | 2015 |
| Pearl Island | RCP 2.6 | N/A |  |
| RCP 8.5 | *Pollachius virens* | 2062 |
| Point Michaud and Basque Islands | RCP 2.6 | N/A |  |
| RCP 8.5 | *Gadus morhua* | 2076 |
| Port Joli and Surrounding Areas | RCP 2.6 | *Amblyraja radiata* | 2067 |
| RCP 8.5 | *Amblyraja radiata* | 2048 |
| Roseway Bank | RCP 2.6 | *Chionoecetes opilio* | 2027 |
| RCP 8.5 | *Chionoecetes opilio* | 2018 |
| Sable Island Bank | RCP 2.6 | *Chionoecetes opilio* | 2019 |
| RCP 8.5 | *Chionoecetes opilio* | 2015 |
| Sambro Bank Sponge Conservation Area | RCP 2.6 | *Chionoecetes opilio* | 2015 |
| RCP 8.5 | *Chionoecetes opilio* | 2015 |
| Sambro Ledges - Prospect | RCP 2.6 | *Chionoecetes opilio* | 2027 |
| RCP 8.5 | *Chionoecetes opilio* | 2018 |
| Scotian Gulf | RCP 2.6 | *Chionoecetes opilio* | 2015 |
| RCP 8.5 | *Anarhichas lupus* | 2015 |
| Southren Bight | RCP 2.6 | N/A |  |
| RCP 8.5 | *Pollachius virens* | 2048 |
| South Grand Manan | RCP 2.6 | *Anarhichas lupus* | 2015 |
| RCP 8.5 | *Amblyraja radiata* | 2015 |
| St Anns Bank Marine Protected Area | RCP 2.6 | *Chionoecetes opilio* | 2067 |
| RCP 8.5 | *Chionoecetes opilio* | 2039 |
| The Gully Marine Protected Area | RCP 2.6 | *Chionoecetes opilio* | 2020 |
| RCP 8.5 | *Chionoecetes opilio* | 2015 |
| Western Emerald Bank Conservation Area | RCP 2.6 | *Chionoecetes opilio* | 2015 |
| RCP 8.5 | *Chionoecetes opilio* | 2015 |
| Western Jordan Basin | RCP 2.6 | *Anarhichas lupus* | 2015 |
| RCP 8.5 | *Amblyraja radiata* | 2015 |

The draft network of MPAs/OECMs on the Scotian shelf Bay of Fundy Bioregion and 30 species observed within were assessed based on averaged climate model projections under two emissions scenarios RCP 2.6 and RCP 8.5 to determine species ToE for each site. For both emissions scenarios it was found that MPA/OECM sites in the Western Scotian shelf region had the highest percentage of species lost on average, followed by the Bay of Fundy and Eastern Scotian shelf regions, respectively (Figure ). Under the RCP 2.6 emission scenario, the total average species loss across the draft network was around 25% and under the RCP 8.5 emission scenario the total average species loss was around 45% network wide (Figure ). Under RCP 2.6 MPA/OECM sites: LCCA (Eastern Scotian shelf), GB (Western Scotian shelf), and JBCA (Western shelf) were shown to have the highest species loss amongst the sites (Figure ). Under RCP 8.5 the MPA/OECM sites: LCCA (Eastern Scotian shelf), GB (Western Scotian shelf) and SBSCA (Western Scotian shelf) were shown to have the highest species loss amongst the sites (Figure ). MPA/OECM sites: BINWA, CB, MEMPA, KSNPHS, and BPI (see Table 3 for full names) were shown to have no species loss to the year 2100 under both emissions scenarios, MPA/OECM sites: SB, PI, and PMBI were shown to have no species loss under the RCP 2.6 emissions scenario but have species loss under the RCP 8.5 emissions scenario (Figure ).

## Tables

Table 3. MPA/OECMs names, abbreviated names, number of species observed within (from OBIS), longitude and latitude, region, and the area covered by each site in the Scotian shelf Bat of Fundy bioregion draft network

4. Discussion

First sentences: Reiterate goal of the study and how you accomplished the goal, then note details. From Intro: “The aim of this study is to estimate the time of emergence of 30 fish and invertebrate species of interest (depleted species, species at risk, and commercially important species) within each of the existing and proposed MPA/OECM site boundaries in the draft conservation network design for the Scotian Shelf (Figure 1) under six projections of future sea surface temperature.”

First paragraph: compare RCP’s.

Results show that, under a scenario of reduced emissions (RCP 2.6), the majority (>50%) of species are retained within the boundaries of the draft conservation network (Figure X). This result is consistent with the IPCC’s 2021 report and with several other studies indicating muted distribution shifts under RCP 2.6 compared to RCP 8.5 (e.g., ADD REFS HERE). This suggests that, if targets for emissions reductions are met, the Scotian Shelf-Bay of Fundy bioregional conservation network, as it is currently designed, may …. BUT, recent studies indicate the globe is offtrack to meet these targets, suggesting the RCP 8.5 results may still be more likely….

Some example refs:

[Forecasting shifts in habitat suitability across the distribution range of a temperate small pelagic fish under different scenarios of climate change - ScienceDirect](https://www.sciencedirect.com/science/article/pii/S004896972105244X)

[Wave of net zero emission targets opens window to meeting the Paris Agreement | Nature Climate Change](https://www.nature.com/articles/s41558-021-01142-2)

[Plausible 2005–2050 emissions scenarios project between 2 °C and 3 °C of warming by 2100 - IOPscience](https://iopscience.iop.org/article/10.1088/1748-9326/ac4ebf/meta)

[Exploring the potential effects of climate change on the Western Scotian Shelf ecosystem, Canada - ScienceDirect](https://www.sciencedirect.com/science/article/pii/S0924796314000529#f0025)

Second paragraph (spatial differences in ToEs (among sites)):

However, under both low and high emissions scenarios, there is a clear southwest to northeast gradient in species’ times of emergence, with greater numbers of species emerging from their thermal niche much sooner in the southwest than in the northeast (Figure X). This result is consistent with many studies that have documented the steep temperature gradient, and consequent gradient in species assemblages, that characterizes the Scotian Shelf- Bay of Fundy bioregion (e.g., Stanley et al. 2018), and those that have indicated the southern range limit of many of the Scotian Shelf’s resident species occurs around the southwestern reaches of the bioregion (e.g., Shackell et al. 2014; see if you can find one more ref here). The most vulnerable sites (besides the Lophelia Coral Conservation Area, LCCA, which is a very small, Xkm2, area at the northeastern edge of the Scotian Shelf with only X of our species of interest present) predicted to have temperatures outside the tolerance limits of more than X% of resident species assessed here by 2025, are XXX, XXX, and XXX. XXX is positioned where warm waters derived from the Gulf Stream flow into the Gulf of Maine (Brickman et al., 2018; Brickman et al. 2021), and both XXX and XXX are located in the Bay of Fundy, which is presently the warmest part of the bioregion and predicted to warm the most rapidly due to its connection with the Gulf of Maine (Brickman et al., 2018; Brickman et al. 2021).

[ELEMENTA\_D\_20\_00055 1..15 (silverchair.com)](https://watermark.silverchair.com/elementa.2020.20.00055.pdf?token=AQECAHi208BE49Ooan9kkhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAAuYwggLiBgkqhkiG9w0BBwagggLTMIICzwIBADCCAsgGCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQMvBaGo70GAcEgSQc3AgEQgIICmZT3kB3Bn_viG3NrnGYKw4ky3KZBrzhzgRaA55UWN5wsUXCoIu2SH5UrxoAuPfqWaMDzX_UvcP0jR39hIQehbQzqUyu_SPjcmD9Spg24mQxBJtm8NZzwYNG0fJvh75T14dZDELu6W9qtf6C068qYi2gIKxAgzcytmw51TjITxCNYXLtjn2T36_FIWY5JLo7IT2WAJPg6_r7TktLx9lOOg5nrgFNT9ASdjVnlkpVNSUTAZInaOzYOHhBW3xE9iDv9hoCZ-HOCQmsTvE9yQPy4Pim5FokEs6OMEFvJDleD2cBHPvH8UZvQ2QXWrVS1Q9jJPiA_l5l8SyHToG04h7czaB2AhUXLfqiQ_Xr_KU6gnM_W8Sb-YUNfW01S2Nn3jk0IE1EdZM6qPLFtPeXJ0eIGGbuzMxT9uURhPV9u7rPHwSW3aSJOliR8WADuxvDjmSrSOn4G3TFHrNjNuE-KAHTRH9HX_j-n3wyGaQzc2xd3qnzdJtyK0gVlPbTh4uha97QUUfNvTmCQLd7sNNniV5c7fH0kAq3xXRBx4LvpVY8ITLCPHe6jToKJNdO6MdSaS67JgqLaI0r_-GxfCgpNGKzce4e6CFHQt9S9TJGdpTKDNO_N_gWpJyU7eXD210lBPxPBeip6gKFb-LQXlgj9sUv6mLqAcc_8Qp-CsusWDMuLUxcW441_2dTy1KSql6R4QxCOFV2S_Go5HRi0jyOB36dpmTPyfsZrbOCGCAoGvq1xAoGqkEZvQfeXaTu-uYC8aeyjnbgm5a9Z2UN5t1Gtv3jxJ1WSV1GMWbXaRfsWArZZg3fb9fLG_9imvn_kB4eXMscJtyRNUFDoxNKz57jFQ-b1BU5y0gF1BM1jJbD8CBLkPu4BAiD5RGrZfQSi)

Third paragraph: compare between species… who is the most vulnerable and where? Can reference panel plot Ryan made here (Appendix S1). Discuss what thermal stress can do to a fish/ invert using some of the lit from your intro (below). Discuss how species might still be there, but low density and physiologically stressed (can impact reproduction, body size, etc., therefore impacting vulnerability to other stressors too). Example, Snow Crab (REFS BELOW – scan these and build your snow crab story).

[Potential socioeconomic impacts from ocean acidification and climate change effects on Atlantic Canadian fisheries (plos.org)](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0226544)

[Assessment of Scotian Shelf Snow Crab in 2018 / B.M. Zisserson, B.J. Cameron, A.C. Glass, and J.S. Choi [and] Canadian Science Advisory Secretariat. - Catalogue - Canada.ca](https://science-catalogue.canada.ca/record=4098747~S6)

[Stock Status Update of Scotian Shelf Snow Crab (Chionoecetes opilio, O.Fabricius) (dfo-mpo.gc.ca)](https://waves-vagues.dfo-mpo.gc.ca/Library/40989574.pdf)

Points (with citations) from Introduction to reiterate here (but change the wording and context):

* When an organism is living at its upper or lower temperature limit, oxygen demand increases, often exceeding the organism’s ability to maintain it, causing reduced performance in ventilation and circulation (Pörtner, 2001; Pörtner & Farrell 2008).
* However, evidence suggests that the rapid environmental changes associated with climate change are already causing geographic shifts in distribution that track shifting distributions of species’ thermal niches (Pinsky et al., 2013; Crozier & Hutchings, 2014; Pinsky et al., 2021).

Fourth paragraph: Caveats: We did not consider other climate factors like oxygen, salinity, sea level, etc. We also did not consider the indirect effects of climate change on the species of interest. For example, warming has been implicated as a factor in the reduction of larval dispersal capacity in fish (e.g., Raventos et al., 2021). Further, some studies have suggested that the expansion of warm-water species distributions towards the poles may outpace the shift of cold-water species, leading to shifts in ecosystem structure (e.g., Pound et al., 2021). Increased predation, competition, or parasitism from incoming warm-water species may also negatively impact the native species of this region (get some refs here on the impacts of invasive species and parasites due to warming on Scotian shelf). This was beyond the scope of this project, BUT put here how, if these things occur, how could this further impact the sites/species identified?

[Temperature reduces fish dispersal as larvae grow faster to their settlement size - Raventos - 2021 - Journal of Animal Ecology - Wiley Online Library](https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/1365-2656.13435)

[Current distributions and future climate‐driven changes in diatoms, insects and fish in U.S. streams - Pound - 2021 - Global Ecology and Biogeography - Wiley Online Library](https://onlinelibrary.wiley.com/doi/abs/10.1111/geb.13193)

Final paragraph: Conclusion: Broad-scale significance/applications of the results and approach. Remember the broad-scale statement from your Intro that I said could be moved here… this is where you talk about how these sorts of studies can be applied elsewhere and why this information is important for MPA planning and management – talk a bit about adaptive management and climate-resilient MPAs.

Tip: when you do literature searches in scholar.google, limit search to 2018+ in the left-hand panel, that way you get all the most recent papers on this topic… this works well since this is a very trendy topic right now 😊 Also make use of “AND” between kaywords to refine your search in the search bar.

## Figures

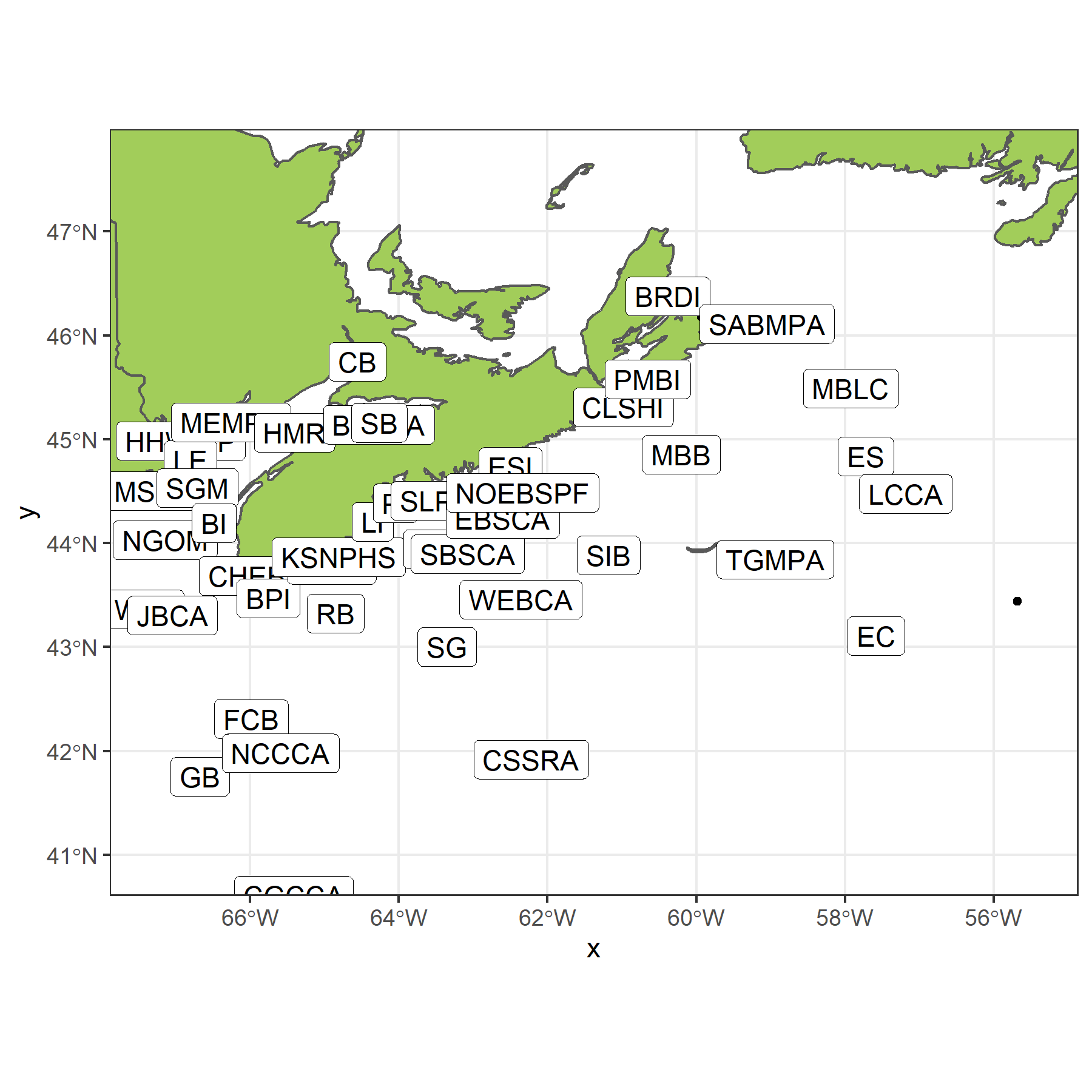
Diagram, engineering drawing

Description automatically generated

**Figure 1**. The Scotian Shelf-Bay of Fundy Bioregion draft conservation network overlaid with a 0.25-degree resolution grid denoting the native resolution of CMIP6 climate projections. The outer boundary of the bioregion is outlined.

Diagram

Description automatically generated



Chart

Description automatically generated

Figure . Depth and temperature ranges of the 30 chosen species (Table 1). A) Depth ranges were obtained from Aquamaps (red) and OBIS (blue). Temperature ranges were obtained from Aquamaps (red) and Shackell et al, 2013 (blue).

Chart, line chart

Description automatically generated

Figure . Time series comparison of average annual temperature of each climate model (AWI, HAD, and IPSL) between emission scenarios RCP 2.6 and RCP 8.5 to the year 2100 in the Scotian shelf Bay of Fundy Bioregion.

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